Supporting Information for "Ganymede MHD Model: Magnetospheric Context for Juno's PJ34 Flyby"

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Introduction

In S1 we provide a detailed description of the magnetohydrodynamic (MHD) model that was used to obtain the results presented in the article. In S2 we describe the numerical solution process by utilizing the PLUTO code. S3 is a movie that visualizes the modeled three-dimensional context of Juno's trajectory during its PJ34 flyby.

Text S1, Model Description

We describe Ganymede's space environment by adopting a magnetohydrodynamic (MHD) model. Since the upstream conditions in Jupiter's magnetosphere can be assumed constant during the time scales of the local interaction at Ganymede the model approaches a steady-state solution. Such models have been successfully applied to explain Ganymede's magnetic field and plasma environment (Duling et al., 2014; Jia et al., 2008). In our single-fluid approach the plasma interaction is described by the plasma mass density ρ, plasma bulk velocity $\mathbf{v}$, total thermal pressure p and the magnetic field $\mathbf{B}$. For these variables the ideal MHD equations read in their conservational form, complemented by source terms on their right-hand sides:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left[\rho \mathbf{v}\right] = P m_n - L m_L, \tag{1}$$

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot \left[\rho \mathbf{v}\mathbf{v} - \frac{1}{\mu_0}\mathbf{B}\mathbf{B} + \mathbf{I}(p + \frac{1}{2}\frac{B^2}{\mu_0})\right] = -(L m_L + \nu_n \rho)\mathbf{v}, \tag{2}$$

$$\frac{\partial E_t}{\partial t} + \nabla \cdot \left[(E_t + p)\mathbf{v} - \frac{1}{\mu_0}\mathbf{B}(\mathbf{v}\cdot\mathbf{B})\right] = -\frac{1}{2}(L m_L + \nu_n \rho) v^2 -\frac{3}{2}(L m_L + \nu_n \rho)\frac{p}{\rho} + \frac{3}{2}(P m_n + \nu_n \rho)\frac{k_B T_n}{m_n}, \tag{3}$$

$$\frac{\partial \mathbf{B}}{\partial t} - \nabla \times \left[\mathbf{v} \times \mathbf{B}\right] = 0. \tag{4}$$

The total energy $E_t = \frac{1}{2}\rho v^2 + \frac{3}{2}p + \frac{1}{2}\frac{B^2}{\mu_0}$ is composed of the kinetic, thermal and magnetic energy. The model features approximations of physical processes that build on the model of Duling et al. (2014). Momentum loss due to particle collisions with neutral O_2

molecules is characterized by a collision frequency ν_n as a function of a radially symmetric atmosphere and for expected plasma velocities we adopt a constant cross section.

Photo-ionization of the atmosphere as well as recombination in areas of high density are characterized by the production rate P and loss rate L respectively. These parameterizations are explained in detail in Duling et al. (2014). For all chemical processes we assume the mass of O_2 molecules $m_n = m_L = 32$ amu, neglecting the recently detected H_2O component on the sub-solar side (Roth et al., 2021). The last term in the energy equation (3) considers the transfer of thermal energy from the neutral atmosphere to the plasma. Since the thermal energy of the atmosphere is low compared to the plasma, this term is expected to be negligible. We keep it for completeness and set the atmosphere's temperature to $T_n = 100$ K (Marconi, 2007) while k_B is the Boltzmann constant.

Ganymede's intrinsic magnetic field is described by dipole Gauss coefficients $g_1^0 = -716.8$ nT, $g_1^1 = 49.3$ nT, $h_1^1 = 22.2$ nT as derived by Kivelson, Khurana, and Volwerk (2002). Within their uncertainties, dipole coefficients updated from Juno data by Weber et al. (2022) have equal values. Quadrupole models either neglect an induction response of an ocean (Saur et al., 2013) or do not significantly improve the fit to available data. During Juno's visit Ganymede was near the center of the current sheet where the induction response is close to minimum. In our model the induced field has a maximum surface strength of 15.6 nT.

The upstream plasma conditions are adjusted to the flyby situation as discussed in Section 4.1.

Text S2, Numerical Solution Process

We perform numerical simulations to obtain an approximate solution for equations (1-4). While we utilized the ZEUS-MP code (Hayes et al., 2006) for our former work, we now present results obtained with the PLUTO code (Mignone et al., 2007). This code is broadly used in the plasma science community and gives us the advantage to compare and validate our model results obtained by two different and independent numerical solvers (Section 4). PLUTO is an open-source software designed to solve hyperbolic and parabolic systems of PDE's for astrophysical fluid dynamics. In contrast to ZEUS-MP's finite difference approach it uses the finite volume method. In our application we utilize a piece-wise linear, 2nd order reconstruction of the variables in the cells, the Harten, Lax, Van Leer solver for the Riemann problem to calculate the fluxes at the cell interfaces and a 2nd order Runge Kutta scheme for the integration over time. Unfeasible time steps and instabilities caused by possibly emerging vacuums are prevented by ensuring a minimal mass density and thermal pressure of 5% of the upstream value.

For the numerical solution we divide the space between Ganymede's surface and 70 Ganymede radii (R_G) into a grid with spherical geometry and a longitudinal and latitudinal resolution of 2.8°. Below 1.2 R_G the radial resolution equals 0.02 R_G and increases exponentially afterwards up to 1.4 R_G, resulting in 2.1 million cells in total. Representing Ganymede's surface, the inner boundary absorbs the incoming plasma. This is considered by applying open conditions for the plasma variables in addition to forcing the radial velocity component to be zero or negative. Ganymede's icy, electrically non-conducting crust cannot carry electric currents. This property directly affects the near surface magnetic field and is considered through isolating boundary conditions derived in Duling et al. (2014). At the outer boundary we use fixed boundary values equal to the upstream conditions on the upstream side and open conditions on the downstream side.

Movie S3.

The movie illustrates the three-dimensional geometry of Ganymede's magnetosphere in reference to Juno's trajectory (red line) for the time around closest approach. The green surface represents the extent of the closed field line region. The blue surfaces represent the regions with open field lines that connect Ganymede's polar regions with Jupiter and correspond to the Alfvén wings. The white tubes show selected closed and open field lines and the dark tubes show field lines that are seeded on Juno's trajectory. Outside of the magnetosphere these field lines are unconnected and inside the magnetosphere they end at Ganymede's surface, representing Juno's magnetic footprint. Auroral oxygen emissions are displayed on Ganymede's surface as observed by Juno's UVS instrument (Greathouse et al., 2022).

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